Tommy Gold Revisited: Why Does Not The Universe Rotate?

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Understanding gravitational collapse requires understanding how $\sim 10^{58}$ nucleons can be destroyed in $\sim 10^{-5}$ seconds. The recent proposal that the endpoint of gravitational collapse can be a "dark energy star" implies that the mass-energy of the nucleons undergoing gravitational collapse can be converted to vacuum energy when one gets near to conditions where classical general relativity predicts that a trapped surface would form. The negative pressure associated with a large vacuum energy prevents an event horizon from forming, thus resolving the long-standing puzzle as to why gravitational collapse always leads to an explosion. An indirect consequence is that the reverse process - creation of matter from vacuum energy - should also be possible. Indeed this process may be responsible for the "big bang". In this new cosmology the observable universe began as a fluctuation in an overall steady state universe. The fluctuations in the CMB in this picture are the result of quantum turbulence associated with vorticity. This explanation for the CMB fluctuations is superior to inflationary scenarios because there is a natural explanation for both the level of CMB fluctuations and the deviation from a scale invariant spectrum at large scales.

I. INTRODUCTION

One of the oldest conundrums of cosmology is why does not the universe rotate? Rotation and magnetic fields are ubiquitous features in the cosmos, so it seems a little odd that rotation does not play a role on a cosmological scale. For example, one might wonder why rotating cosmological models such as the Gödel universe are not useful for describing the

large-scale structure of the universe. Of course, the Gödel solution of the Einstein equations represents a steady state universe, so it would come into conflict with all the astrophysical evidence that the universe is evolving with time. In this talk we will argue that there is a very natural way to reconcile the evidence for a big bang with the existence of rotation on a cosmological scale, and that the failure of astrophysicists to understand the role of rotation on cosmological scales is due to their misplaced faith in the physical correctness of general relativity (GR) under all circumstances.

Actually, as has been emphasized by Robert Laughlin, Emil Mottola, and the authors in several papers over the past few years, it cannot possibly be true that general relativity is always correct for macroscopic length scales. In particular, in contrast with the commonly held belief that Einsteins theory of general relativity only fails for length scales approaching the Planck length $\sim 10^{-33}$ cm, we have argued that certain macroscopic features of space-times that are allowed by general relativity do not occur in the real world because they are in conflict with ordinary quantum mechanics. The most notable of these features are event horizons and closed time-like curves. The reason these features conflict with quantum mechanics can be simply stated: these features are inconsistent with the existence of a universal time based on atomic clocks. Quantum mechanics requires for its definition a universal time based on the synchronization of atomic clocks. However, synchronization of clocks of any kind is not possible in rotating space-times, and in the case of space-times containing event horizons synchronization of clocks fails at the event horizon.

One of us suggested some time ago [1] that the way nature establishes a universal time for space-time is via the existence of off-diagonal long range order (ODLRO) for the vacuum state. In particular, if one thinks of the vacuum state as a kind of superfluid, then the long-range correlations between the constituent particles of the vacuum state in effect establish a universal time for both the vacuum state and its excitations. The macroscopic behavior of fluids is usually described using classical equations. However, as was first clearly explained by Feynman [2], in the case of superfluids there are circumstances where quantum mechanics is essential for describing the macroscopic behavior. In the context of a superfluid theory of space-time it turns out that these circumstances correspond precisely to the appearance of either event horizons [3, 4] or closed time-like curves [5]. The need to use quantum mechanics to describe macroscopic space-time in these particular circumstances signals a failure of classical GR.

The failure of a classical description of space-time near to where GR predicts that an event horizon should occur solves a long-standing puzzle of astrophysics; namely, how does it happen that during the gravitational collapse of a massive stellar core the baryon number of the core disappears in $\sim 10^{-5}$ sec? Classical GR cannot be regarded as providing a complete physical description of gravitational collapse because it does not tell us what happens to the baryon number of the collapsing matter. On the other hand, within the framework of a superfluid description of space-time there is a direct link between the evolution of baryon number in a region where GR breaks down and the physics of elementary particle collisions at energies approaching the Planck energy $\sim 10^{19}$ GeV .

According to grand unified theories of elementary particle interactions, such as the Georgi-Glashow $SU(5)$ model, quarks can be transmuted into leptons and mesons as a result of collisions at energies approaching the Planck energy. The net result [6] is that during gravitational collapse nucleons are converted into positrons as one approaches conditions where general relativity predicts that a trapped surface would form. Under conditions where the matter around the collapsing object has been ejected these positrons can escape and form a halo around the collapsed object. Amusingly, x-ray telescopes have detected a halo of 511 keV positron annihilation radiation surrounding the center of our galaxy where a massive compact object is thought to reside. Whether these positrons are emitted from the compact object Sag A* remains to be confirmed, but at the present time there is no conventional explanation for the positrons near to the galactic center [7]. It would be wonderful if the positron halo at the galactic center turned out to be direct evidence for the conversion of baryon number into lepton number predicted by Georgi and Glashow.

II. DESTRUCTION AND CREATION OF MATTER

In the superfluid picture of space-time event horizons do not occur. Instead when one approaches a condition where classical GR predicts that a trapped surface would form, a quantum critical layer of finite thickness forms where the red-shift becomes large but not infinite [3, 4]. The thickness of this layer grows as its radius increases [4], so that in the limit where space-time is nearly flat the region of space in which GR breaks down due to proximity to an event horizon becomes macroscopically large. The behavior of matter near to a quantum critical point is to a large extent universal, so one can infer that nucleons

passing through such a region will decay into positrons and mesons. One can also surmise that the same sort of process that occurs in an optical fiber where photons are converted into a coherent squeezed state of light can occur in the quantum critical region, and allow the energy of quark pairs to be converted into vacuum energy. In the context of the gravitational collapse of a stellar core this process would allow the conversion of nucleon mass-energy into vacuum energy, and would lead to a giant explosion since the vacuum energy has zero entropy. In accordance with the second law of thermodynamics the entropy of the collapsing matter must necessarily be expelled as an entropy exhaust.

It is tempting to identify the entropy exhaust associated with the formation of a dark energy star with those supernovae explosions where it has been speculated for the last half-century that a black hole was formed. One problematic aspect of the black hole hypothesis, though, has been that despite decades of effort no explanation has ever been found to why the formation of a black hole should lead to an explosion. Numerical hydrodynamic calculations based on general relativity predict that when the mass of the collapsing stellar core exceeds a few solar masses the stellar core simply falls inside a trapped surface in a finite proper time from which nothing can escape, and there is no explosion. On the other hand, the dark energy star hypothesis offers a simple explanation as to why stellar collapse always leads to a vigorous explosion as observed from afar. Indeed, the dark energy star prediction is that it should be difficult, just based on looking at the visible phenomena of the collapse, to tell whether a neutron star or a dark energy star was formed. In particular, the visible light phenomenology resulting from the formation of a dark energy star should resemble what happens when a neutron star is formed, because in both cases a low entropy residual object is formed and the entropy of the collapsing stellar core must be removed by the ejected matter. Of course, the physical nature of a dark energy star is quite different from a neutron star, and this difference might be apparent in the neutrino emissions or gravitational radiation accompanying the supernova explosions. To date neutrino data is available for only one supernova, $1987A$, and it is perhaps not surprising that the results do not agree with what is expected on the basis of a conventional picture for gravitational collapse [8].

The microscopic processes involved in the disappearance of nucleons during the formation of a dark energy star are for the most part time reversible. This means that a time-reversed process whereby vacuum energy is converted into quarks, leptons, and gamma rays is theo-

retically possible. The stability of the normal vacuum state would preclude such a process from occurring under ordinary circumstances. In addition, theoretical calculations indicate that dark energy stars in isolation are stable at zero temperature. On the other hand, gravitational collapse of an assembly of dark energy stars may offer an opportunity to convert the vacuum energy stored in the mass of the dark energy stars into ordinary matter energy.

The vacuum energy density ρ_v inside a dark energy star with radius $R_{_H}$ will be given by [3, 4]

$$\rho_v = \frac{c^4}{8\pi G} R_{_H}^{-2}, \tag{1}$$

where G is Newtons constant. The close packing of N dark energy stars, each with mass $M = \frac{c^2 R_H}{2G}$, will result in an average energy density of

$$\rho_0 = \frac{c^4}{8\sqrt{2}G} R_{_H}^{-2}, \tag{2}$$

within a region of volume $8NR_{_H}^3$. This accumulation of energy density would be gravitationally unstable against continued collapse except for the fact that once the dark energy stars have merged the pressure will be negative and gravity becomes repulsive. However, the energy density (2) is far too high for eq. (1) to be satisfied if $N >> 1$. Therefore if $N >> 1$, almost all the accumulated mass in the merged cluster must somehow be removed.

Eq. (1) predicts that the vacuum energy inside a dark energy star will be ~ 10 times higher than the density of matter inside a neutron star when the mass of the dark energy star is on the order of the Chandrasekhar limit; i.e. ~ 1.4 solar masses. Because the maximum mass of a neutron star is only slightly higher than the Chandrasekhar limit, there is thus reason to suspect that the maximum possible density for neutron stars marks a transition between a vacuum where ordinary matter is stable and a vacuum containing only dark energy. That is, the Chandrasekhar limit may perhaps be interpreted as the quantum gravity Gibbs criterion for a phase transition between nuclear matter and a state with no ordinary matter but a large vacuum energy [9]. If this interpretation is correct, then the transition between a state with a large vacuum energy and a state with ordinary matter will only occur rapidly if the merged energy density (2) exceeds by some margin the energy density of the nuclear matter in neutron stars. At lower merged densities the creation of ordinary matter will not be efficient, and we would expect that the reversal of gravitational collapse would result in an expanding cloud consisting mainly of massive dark energy stars.

An analytical model that one might use to describe the evolution of space-time during the conversion of the mass of a collapsing cluster of dark energy stars into radiant energy has recently been provided by Joshi and Goswami [10]. In their model the pressure varies with radius within a spherically symmetric cloud of matter, but becomes negative in the inner part of the cloud when the ratio of the co-moving circumference $2\pi R$ to coordinate radius within the cloud falls below a certain value. Initially this ratio is close to 2π, but this ratio approaches zero for all R as the collapse proceeds. In order to satisfy the Einstein equation

$$P = -\frac{\dot{m}(R)}{4\pi R^2 \dot{R}}, \tag{3}$$

the mass $m(R)$ contained within a volume with circumference $2\pi R$ must decrease with time if the pressure $P(R)$ is negative. In the model of Joshi and Goswami the conversion of the mass $m(R)$ into radiation is accomplished by matching the interior metric to a Vaidya metric at the outer boundary of the collapsing matter (cf. Fig. 1). Eventually all the mass-energy in the collapsing cloud is converted into radiation. This model may describe the endpoint of the collapse of a cloud of dark energy stars in the case where the merged density (2) is much larger than the density of neutron stars. In reality, reversal of the gravitational collapse of a massive cloud will result in the production of dark energy stars as well as radiation, but the Vaidya metric will still provide a good initial description for local space-time if the energy density post collapse is dominated by radiation.

III. A NEW VERSION OF THE STEADY STATE UNIVERSE

In the original steady state universe of Bondi, Gold, and Hoyle it was assumed that matter is being created at a rate that on average is the same everywhere. It was subsequently suggested by Hoyle, Burbridge, and Narlikar [11] that matter creation processes might also lead to anomalous explosive events within galaxies. Apparently it did not occur to them that matter creation might be responsible for the big bang itself. Instead, they argued that the observed evolution of the universe is an illusion. This is not our position.

Our position is that the big bang is an illusion only in the sense that the universe we observe may not be representative of the universe as a whole. At the time of big bang nucleosynthesis the entire observable universe was smaller in size than the distance to the

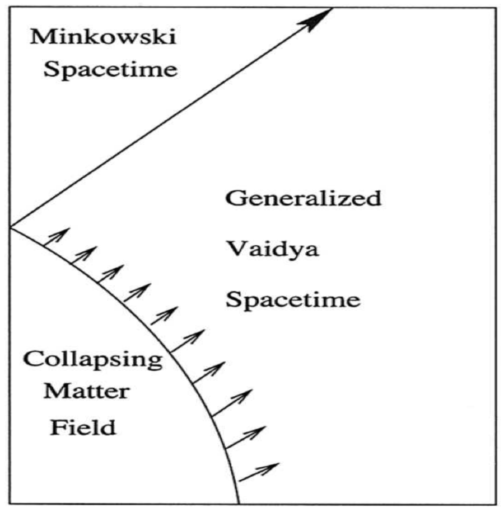

FIG. 1: Schematic of the behavior of space-time in the analytical model of Joshi and Goswami that simulates the conversion of vacuum energy into radiation.

nearest star. On the other hand, evidence that the value of the vacuum energy is constant with time [12] points to a steady state universe with a scale size that is constant in time. In particular, the coincidence between the vacuum energy predicted by eq. (1), where R_H is the current radius of the observable universe, and the value of the vacuum energy inferred from observations of distant supernovae suggests that in the big picture *we live in a quasi-steady state universe, with a finite size on the order of* 10 *gigaparsecs* [4, 9, 13]. Concomitantly the universe we observe may just be the long time result of the evolution of a localized fluctuation within the framework of a much larger universe whose overall size does not change with time.

The explosive nature of the fluctuation leading to the expanding and evolving universe that we observe can be naturally explained if it is assumed that this fluctuation had its origin in the gravitational instability of a cluster of dark energy stars. A cluster of separate dark energy stars will not be stable against gravitational collapse when the gravitational binding of the cluster overcomes the expansion velocities of the stars in the cluster. Moreover, once the dark energy stars in the collapsing cluster begin to merge together, then the dynamics of the collapse will change dramatically. In particular, one will evolve from a situation where the mean pressure in the cluster is near to zero to a situation where the mean pressure is large and negative; resulting in a strong reversal from contraction to expansion because the gravitational effect of negative pressure is repulsive. If the average energy density at the time of maximum collapse exceeds the energy density of matter in neutron stars, then we

would expect that a substantial fraction of the initial total mass of the cluster of dark energy stars would be converted into ordinary radiation and matter. This, of course, would match nicely what we know about the universe that we observe, because we know that during its initial phase the big bang was dominated by gamma radiation and the initial density must have been high enough to permit nucleosynthesis of deuterium and helium.

If this picture turns out to be correct, then the big bang did not begin with infinite density, but with densities only modestly above those that occur in neutron stars. In addition, the familiar expansion of the observable universe would have begun at a time only slightly earlier than the epoch when He4 and other light isotopes were formed. It is perhaps disorienting that that in our picture there is no place for all the exotic phase transitions that have been imagined to take place in the very early universe. In particular, there is no place for the phase transition leading to inflation.

In our view is that there is no need for inflation; at the present time the large scale properties of the universe are much more easily understood in a framework where the observable universe arises as a fluctuation within an overall steady state universe. The problem of the lack of causal communication between different parts of the universe in the standard big bang cosmology is resolved by the fact that that if the observable universe arises from gravitational collapse rather than emergence from an initial singularity, then all parts of the observable universe would have always been in causal contact. In particular, if one imagines that the observable universe arose as the spherical collapse of a cluster of dark energy stars, then during the later stages of the collapse any point in the cluster will be able to receive light signals from a distance $\pi R(t)$, where $2\pi R(t)$ is the circumference of the collapsing cloud. Thus large regions of the cluster will be able to remain in causal contact at all times during the collapse. Initially all parts of the cluster were in causal contact because in a steady state universe all points within the event horizon are in causal contact. Of course, in a strictly de Sitter universe co-moving particles always move away from each other and eventually fall out of contact. However, this is not true in a rotating steady state universe [14], and a fortiori it is not true for co-moving particles undergoing gravitational collapse. Thus the necessity for an inflationary epoch in the initial expansion of the observable universe is completely removed.

What role does rotation play if the big bang originates as a collapsing density fluctuation in a steady state universe? As noted earlier it is somewhat surprising that the observable

universe does not rotate. In a superfluid such as liquid helium rotation is carried by quantized vortices [2]. In the superfluid picture of space-time rotation would also be carried by vortex-like objects [5]. Actually these gravitational vortices are more like the Abrikosov vortices in a superconductor than the Feynman-Onsager vortices in liquid helium because of the presence of frame-dragging [5]. In the limit where the density of parallel spinning strings is high the spatial averaged space-time metric approaches that of a Gödel-like solution to the Einstein equations [5]. Since the number of vortices will be conserved during the collapse leading up to the big bang and subsequent expansion, the question then is why does not the observable universe also look like a Gödel universe? Remarkably, this question has a very natural resolution in the context of the superfluid picture for space-time [5]. If one starts to rotate a container of liquid helium very rapidly one typically finds that the vortices start to meander, become tangled, and the motion becomes turbulent. Therefore, even if the universe as a whole rotated, in a region of space-time that was undergoing rapid gravitational collapse the perfect alignment of the spinning string vortices that would give rise to a Gödel-like metric will be lost, and be replaced by quantum turbulence. Does this have any observable consequences? As it happens quantum turbulence in a superfluid has many characteristic features. Because there is no natural length scale in a superfluid except for the finite size of the container, there are length scales where the turbulence has a scale invariant spectrum. In addition, if one assumes that the fluctuations in density are entirely due to random variations in vorticity, then the relative level of energy fluctuation in the vorticity field will be on the order of $(\frac{\Delta v}{c})^2$, where Δv is the r.m.s. deviation in galactic velocity from the Hubble flow [9].

Of course, when one considers fluctuations in the CMB for the largest length scales, the fluctuations may be expected to remember the fact the big bang originated in an overall steady state universe where the vorticity is not random, but a smooth function of position as in a Gödel-like universe . At these largest scales the turbulence will be suppressed and the vorticity will have a definite orientation in space. As it happens this is just what is observed [15].

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